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The QUIJOTE experiment: project overview and first results

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Abstract

QUIJOTE (Q-U-I JOint TEnerife) is a new polarimeter aimed to characterize the polarization of the Cosmic Microwave Background and other Galactic and extragalactic signals at medium and large angular scales in the frequency range 10-40 GHz. The multi-frequency (10-20 GHz) instrument, mounted on the first QUIJOTE telescope, saw first light on November 2012 from the Teide Observatory (2400 m a.s.l). During 2014 the second telescope has been installed at this observatory. A second instrument at 30 GHz will be ready for commissioning at this telescope during summer 2015, and a third additional instrument at 40 GHz is now being developed. These instruments will have nominal sensitivities to detect the B-mode polarization due to the primordial gravitational-wave component if the tensor-to-scalar ratio is larger than $r = 0.05$.

1 Introduction

The Cosmic Microwave Background (CMB) is recognised as one of the most powerful cosmological probes. The study of temperature anisotropies by missions like *WMAP* [1] or *Planck* [16], and previous ground-based and balloon-born experiments, have reached levels of sensitivity and angular resolution that have allowed the determination of the main cosmological parameters with accuracies close to 1%. The CMB polarization anisotropies also encodes a wealth of cosmological information. Not only the E-mode polarization have allowed to tighten the cosmological constraints by breaking degeneracies between parameters, but the detection of the B-mode polarization may provide a confirmation of the existence of primordial gravitational waves created by inflation, the epoch of exponential expansion in the primordial Universe [12, 20]. Specifically-targeted experiments like QUIET [18] or BICEP [2] have already started to put constraints on the tensor-to-scalar ratio, r, the parameter that is used to parameterise the amplitude of the B-mode signal. Others like SPTpol [9] or POLARBEAR [15] have measured the small-angular scale B-mode component which is not primordial but originated by the lensing of the E-mode polarization by large-scale-structure. Recently, the first primordial B-mode detection was claimed in data from the BICEP2 experiment at 150 GHz, with a level of the tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$ [3]. However, data from the *Planck* satellite have shown that the level of polarized dust emission in the region of the sky covered by BICEP2 could form a significant component of the measured signal [17], thus causing a likely reduction in the level of cosmological signal that can be inferred from the BICEP2 results.

It is well recognised that any unambiguous detection of the B-mode anisotropy requires a detailed assessment of the level of foreground contamination and ideally confirmation by independent experiments operating at different frequencies. The QUIJOTE (Q-U-I JOint TEnerife) experiment [19, 13], thanks to its wide frequency coverage (10-40 GHz), will provide

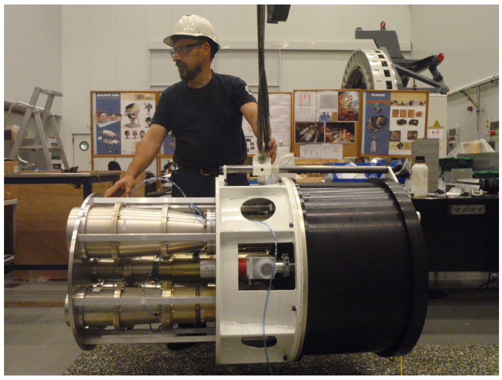

Figure 1: Left: QT1 (background) and QT2 (front) inside the enclosure, at the Teide observatory. Right: MFI, during integration tests (December, 2011).

the characterization of the polarization of the synchrotron and anomalous microwave emission (AME), and of the B-mode signal down to a sensitivity of $r = 0.05$. Updated information of the project can be found in `http://www.iac.es/project/cmb/quijote`.

2 Project baseline

The QUIJOTE experiment is a scientific collaboration between the Instituto de Astrofísica de Canarias, the Instituto de Física de Cantabria, the IDOM company, and the universities of Cantabria, Manchester and Cambridge. The project consists of two telescopes and three instruments covering the frequency range $10-40$ GHz, with an angular resolution of $\sim 1^\circ$, and located at the Teide observatory (2400 m) in Tenerife (Spain). This site provides excellent atmospheric conditions for CMB observations, as demonstrated by previous experiments (Tenerife experiment, IAC-Bartol, JBO-IAC interferometer, COSMOSOMAS, VSA). Data obtained with the first QUIJOTE experiment throughout one year shows that the zenith atmosphere temperature is on average ~ 2 K at 11 GHz and $\sim 4-6$ K at 19 GHz, while the PWV column density is typically between 2 and 4 mm.

The first QUIJOTE telescope (QT1) is currently fitted with the multi-frequency instrument (MFI), which has four frequency bands centred in 11, 13, 17 and 19 GHz, respectively. It saw first light on November 2012, and ever since is performing routine observations of different fields. Some results obtained with this experiment will be presented in Section 4. The second QUIJOTE telescope (QT2) was installed at the observatory on July 2014. This telescope will be fitted with the thirty-gigahertz instrument (TGI), consisting in 31 polarimeters at 30 GHz and which will start commissioning on April 2015. A third set of detectors, the forty-gigahertz instrument (FGI) is being constructed at the time of writing (January 2015). Figure 1 shows photos of QT1, QT2 and the MFI.

In Table 1 we show the nominal characteristics of the three QUIJOTE experiments.

The noise equivalent power for each frequency band is computed as:

$$\mathrm{NEP_{MFI}} = \frac{T_{\rm sys}}{\sqrt{\Delta\nu}} \quad , \quad \mathrm{NEP_{TGI,FGI}} = \sqrt{2}\frac{T_{\rm sys}}{\sqrt{\Delta\nu N_{\rm chan}}} \quad , \tag{1}$$

where $T_{\rm sys}$ stands for the total system temperature, $\Delta\nu$ is the bandwidth and $N_{\rm chan}$ the number of channels (computed here as the number of horns times the number of output channels per horn). The NEPs are different for MFI compared to TGI and FGI because of their different strategies for measuring the polarization. In the MFI it involves differentiating pairs of channels, whereas the TGI and the FGI will make use of electronic modulation providing an instantaneous measurement of Q and U for each channel. The MFI parameters measured using real observations are in good agreement with the nominal parameters shown in Table 1. In particular, the measured Q and U NEPs are in the range $644 - 792$ μK $s^{1/2}$ for different frequency channels. In total intensity I, where the instrument knee frequencies are worse ($f_{\rm k} \sim 0.1 - 1$ Hz for Q and U and $f_{\rm k} \sim 10 - 100$ Hz for I) the instantaneous sensitivities are typically a factor ~ 2.5 worse.

Table 1: Nominal characteristics of the three QUIJOTE instruments: MFI, TGI and FGI. Sensitivities are referred to Stokes Q and U parameters.

	MFI				TGI	FGI
Nominal frequency [GHz]	11	13	17	19	30	40
Bandwidth [GHz]	2	2	2	2	10	12
Number of horns	2	2	2	2	31	31
Channels per horn	4	4	4	4	4	4
Beam FWHM (°)	0.92	0.92	0.60	0.60	0.37	0.28
$T_{\rm sys}$ [K]	25	25	25	25	35	45
NEP [μK $s^{1/2}$]	559	559	559	559	44	52
Sensitivity [Jy $s^{1/2}$]	0.61	0.85	0.62	0.77	0.06	0.07

3 Experimental details

In this section we will present a succinct description of the technical details of the project. More extended details can be found in previous proceedings [7, 10, 11, 8], and in more extended papers that are in preparation.

3.1 Telescopes

Both the QT1 and the QT2 are based on an offset crossed-Dragone optic, with projected apertures of 2.25 m and 1.89 m for the primary (parabolic) and secondary (hyperbolic) mirrors, and provide highly symmetric beams (measured ellipticity > 0.98) with very low sidelobes (≤ -40 dB) and polarization leakage (≤ -25 dB). These mirrors are supported by an altazimuth mount, which allows rotation around the vertical azimuth axis at a maximum

speed of 6 rpm (36°/s). The QT1 and QT2 mirrors have been manufactured with surface accuracies to make them operative up to 90 GHz and 200 GHz, respectively.

3.2 Multi-frequency Instrument (MFI)

This instrument is fed with four independent sky pixels: two of them operate at $10-14$ GHz and the other two at $16-20$ GHz. Each pixel consists in a conical corrugated feedhorn feeding a novel cryogenic on-axis stepping polar modulator. Continuous rotation of these polar modulators, which would allow instantaneous measurements of I, Q and U, is not appropriate for long-term operation of the system, and instead we obtain Q and U by differentiating pairs of channels, and step each modulator with a periodicity of $\sim$ one day in order to reduce systematics. The input orthogonal linear polar signals are separated by a wide-band cryogenic OMT (ortho-mode-transducer) and later amplified through a pair of MMIC (monolithic microwave integrated circuit) 6-20 GHz LNAs (low-noise-amplifiers). These signals are then fed into a room-temperature Back-End module (BEM), where they are further amplified, and later split and passed through a 180°-hybrid, providing four outputs. Each of these outputs is then split and the total band passes spectrally filtered into an upper and lower band, each with a bandwidth of 2 GHz. Therefore, each pixel provides a total of eight channels, four in each of these two bands (see Table 1). The low-frequency pixels provide channels centred in 11 and 13 GHz, and the high-frequency pixels centred in 17 and 19 GHz. In practice, only half of these channels are used to measure Q and U, as the pair differences result in the removal of the $1/f$ noise. The other are affected by different $1/f$ noises as the two channels of each pair pass through different LNAs, and are not used. We plan however to correct for this by the installation of two 90°-hybrids, after which the eight channels will be useful and as a consequence the MFI sensitivity of equation 1 will be improved by a factor 2.

3.3 Thirty-gigahertz Instrument (TGI)

The TGI will be fitted with 31 polarimeters sensitive in the frequency range $26-36$ GHz. As it was said before, the original design of the MFI, based on spinning polar modulators, was found to be not suitable for long-term operations. Thus, in the TGI we have modified the receiver configuration by replacing the polar modulators by a fixed polarizer. The modulation of the polarized signal is achieved by the combination of one 90° and one 180° phase switch. The two states of these switches are exchanged in order to generate four polarization states to minimise the different systematics of the receiver.

3.4 Forty-gigahertz Instrument (FGI)

The FGI will be fitted with 31 polarimeters working in the frequency range $35-47$ GHz. The conceptual design is the same as in the TGI.

4 Science cases and first results

4.1 Core science

The QUIJOTE project is envisaged to achieve two primary scientific goals:

- to detect the B-mode signal from primordial gravitational waves down to a sensitivity $r = 0.5$;
- to determine the polarization properties of the synchrotron and anomalous microwave emissions from our Galaxy at low frequencies ($10 - 40$ GHz).

To meet these goals we will perform two polarization surveys:

i) a wide Galactic survey. It covers around $20,000$ deg^2 and after 6 months of observations with each instrument it will have a final sensitivity of ~ 25 μK/beam at 11, 13, 17 and 19 GHz (MFI), ~ 4 μK/beam at 30 GHz (TGI) and ~ 6 μK/beam at 40 GHz (FGI). Currently we are finalising this survey with the MFI, and have accumulated 5.5 months of data;

ii) a deep "cosmological" survey. It will encompass around $3,000$ deg^2 . Here we shall obtain a sensitivity of ~ 5 μK/beam after 2 years of observations with the MFI (11-19 GHz), and ~ 1 μK/beam with the TGI (30 GHz) and with the FGI (40 GHz).

According to these nominal sensitivities, QUIJOTE will provide one of the most sensitive measurements of the polarization of the synchrotron and anomalous microwave emissions in the frequency rage 10-20 GHz. This is essential as the B-mode signal is known to be subdominant over the Galactic synchrotron in our frequency range. Using the MFI maps from the deep survey we will be able to determine the amplitude and spectral index of the synchrotron emission in every individual pixel, and therefore extrapolate to 30 and 40 GHz in order to correct the TGI and FGI maps. Our goal is to have a residual synchrotron emission at these frequencies below the noise sensitivity of these maps. According to the forecasted sensitivities in the deep cosmological survey, we have shown in a previous publication[19] that after 1 year of effective observing time over $3,000$ deg^2 with the TGI we could reach a sensitivity on the tensor-to-scalar ratio of $r = 0.1$ (at the 95% C.L.). The combination of 3 years of effective time with the TGI and 2 years with the FGI (we can observe simultaneously with the two instruments because we have two telescopes) would allow to reach $r = 0.05$.

4.2 Non-core science

So far, we have invested a significant amount of time to observe different fields related with non-core since programmes. Some of these are:

i) Study of the polarization of the Anomalous Microwave Emission (AME). Currently there is very limited observational information about the level of polarization of the AME,

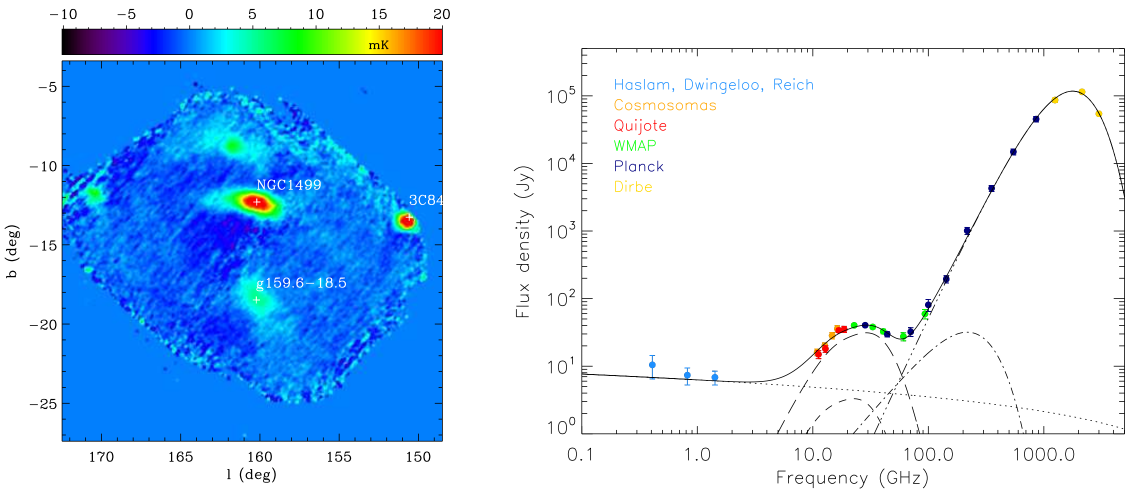

Figure 2: Left: QUIJOTE intensity map at 11 GHz of the region around the Perseus molecular complex (G159.6-18.5). The California nebula (NGC1499) and the quasar 3C84 are also visible. Right: spectral energy distribution of G159.6-18.5. The observed data points are fitted to a combination of free-free emission, two spinning dust components, CMB and thermal dust.

and only upper limits, typically at $< 1\%$ [14, 4], have been published. We have dedicated 149 hours to observe a 250 deg^2-region around the Perseus molecular complex, and have derived upper limits on the AME from G159.6-18.5 of $< 6.3\%$ and $< 2.8\%$ respectively at 12 and 18 GHz, a spectral range that had not been covered before in polarization. In Figure 2 we show the 11 GHz intensity map around this region, and the spectral energy distribution of G159.6-18.5, which represents the most-precise AME spectrum measured to-date, with 13 points begin dominated by AME. These results have been included in a paper that we have recently submitted to MNRAS [6]. We have new observations on G159.6-18.5, amounting to 465 hours, and over a smaller area of ~ 30 deg^2, which could potentially lead to upper limits better by a factor ~ 5.

ii) Study of the WMAP haze in polarization. This is a region with an excess of microwave emission in the region around the Galactic centre, initially found in WMAP data, with a spectrum significantly flatter than synchrotron, and which was later discovered to have a γ-ray counterpart in Fermi data [5]. There is currently a strong debate about its origin. One appealing hypothesis is based on hard synchrotron radiation driven by relativistic electrons and positrons produced in the annihilations of one (or more) species of dark matter particles. QUIJOTE data could have an important contribution here, as it could allow us to measure or to constrain the expected level of polarization of this synchrotron emission. So far we have accumulated 406 hours of data in a ~ 700 deg^2 region around the Galactic centre. In Figure 3 we show QUIJOTE maps at 11 and 13 GHz resulting from 97 hours of data, in comparison with WMAP maps at 23 GHz. A clear correlation can be seen between

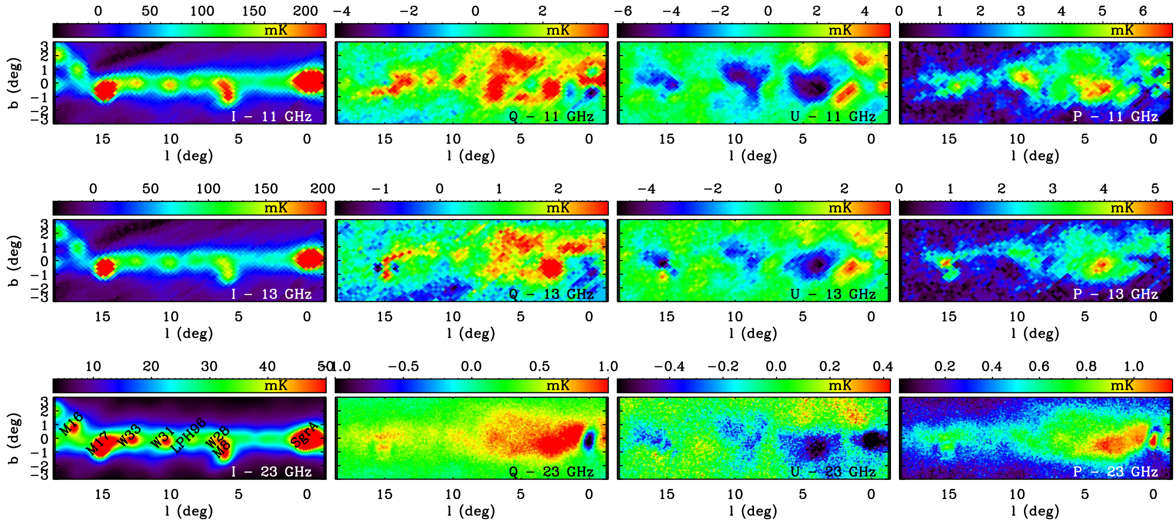

Figure 3: QUIJOTE and WMAP maps along the Galactic centre. We show QUIJOTE maps at 11 and 13 GHz and WMAP maps at 23 GHz. From left to right maps correspond respectively to total intensity Stokes I, Q and U and polarized intensity P. In the WMAP I map we indicate the names of some of the detected regions.

the polarized structures probed by QUIJOTE and WMAP. We are preparing a paper where we will present the results inferred from these observations, and their implications on the physical origin of the haze.

iii) Fan region. The Fan region is one of the brightest features of the polarized radio continuum sky, located around $l = 140°$, $b = 6°$, and long thought to be due to local ($d < 500$ pc) synchrotron emission. This region is an interesting test-bench to assess the potentiality of QUIJOTE to recover diffuse polarized emission. At the time of writing we have accumulated 251 hours of data on a ~ 380 deg^2 region, covering not only the diffuse emission but the point-like emission from the 3C58 SNR.

iv) Study of SNRs. We are interested in the analysis of the spectral energy distributions of SNRs, in order to analyse possible curvatures of the synchrotron spectrum. The wide-survey, which covers the full northern sky, will have enough sensitivity to study different Galactic SNRs. A higher sensitivity is achieved in 3C58 in the Fan observations. We also observe, practically on a daily basis, Tau A, which is our primary calibrator. At the moment we have in total 204 hours in this source, distributed in 631 individual raster scans, each of ≈ 20 min. These observations can be used to study the secular decrease of Tau at the QUIJOTE frequencies. We have also collected 44 hours in IC443 and 75 hours in W63. In Figure 4 we show 11 and 13 GHz maps on IC443, built from 31 hours of data.

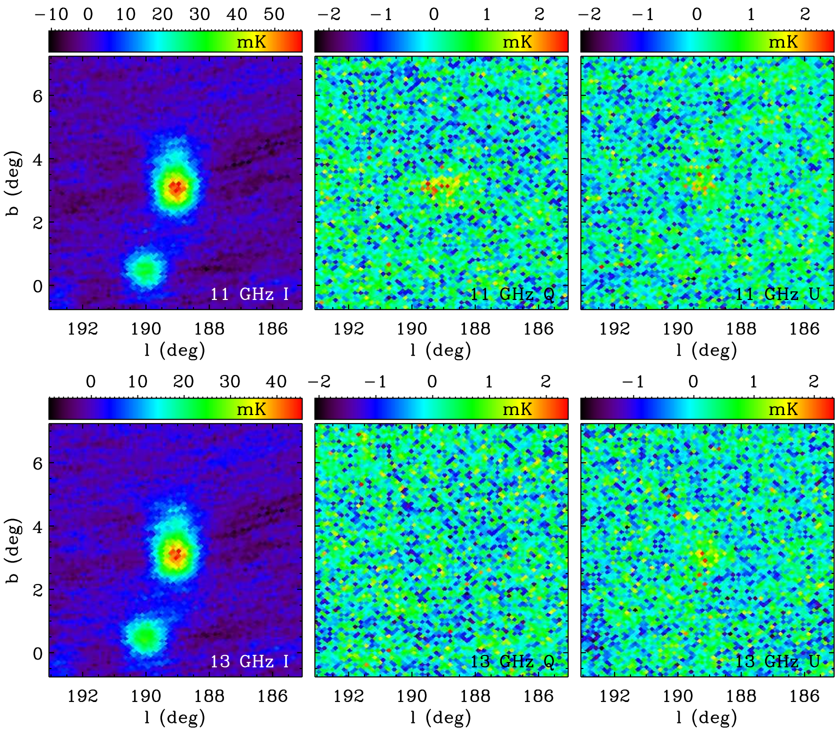

Figure 4: QUIJOTE 11 and 13 GHz maps around the SNR IC443. Polarized emission is marginally seen, with polarization angle $\gamma = -49.8 \pm 19.5^{\circ}$ and $-55.7 \pm 12.0^{\circ}$, respectively at 11 and 13 GHz, values that are compatible with WMAP 23 GHz, $\gamma_{\rm WMAP} = -31.7 \pm 5.7^{\circ}$. The amount of data used to build these maps correspond to 31 hours.

v) Study of the polarization properties of point sources. Apart from the previous SNRs, most of which are point sources, we have observed other Galactic and extra-galactic point sources. In particular: Cas A, which we also use as a calibrator, 3C273, NGC7027 and 3C286. Also, we have been recently awarded 4 hours of VLA time in the semester 2015A, to observe at 30 and 40 GHz pre-selected sources in the deep-survey fields.

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